CRITICAL REVIEW OF AIR POLLUTION DOSE-EFFECT FUNCTIONS

FINAL REPORT
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FOREWORD

This Final Report is published in fulfillment of Council for Environmental Quality Contract No. EQ5AC012, entitled "Assessment and Enhancement of the Utility of Air Pollution Dose-Effect Functions." The study was co-sponsored by the U.S. Environmental Protection Agency, Office of Research and Development.

The material in this volume is organized under five chapters and an appendix, as follows:

- Introduction
- Survey of State of Knowledge
- Analytical Methodology
- Analysis of Selected Functions
- Research Needs
- Appendix: Demonstration of the Utility of Damage Functions

This foreword and an executive summary complete the organization.

The first chapter introduces the major concepts and issues of this study and covers the role and nature of dose-effect functions and their merits and lacks, as well as the purpose, objectives, scope, and organization of the study. The second chapter provides a brief, succinct, but critical survey of the investigations leading to the development of significant dose-effect functions. The methodology chapter discusses the various problems and issues inherent in the development of dose-effect functions, including determination of ambient levels, exposure and effects, types of studies, establishment of dose-effect relationships, and presentation of results. The fourth chapter presents a critical analysis of dose-effect functions pertaining to effects of sulfur dioxide and particulates on human mortality, injury to tobacco leaves by oxidants, and corrosion of zinc by sulfur dioxide and moisture. The last chapter addresses needs for future data collection, development, and investigation, in light of the findings of this study.

This report is designed to assist the investigator of air pollution exposure effects with the development of a valid and useful dose-effect function and to provide the user of these functions with an introduction to their potential and limitations. It has little to offer to the expert in this field. Its major accomplishment is less the advancement of any specific aspect of the state of the art than the assemblage and presentation of much pertinent information in a systematic and readable fashion.

The first attempt to treat a field of inquiry of such broad scope under one cover can not possibly please everyone and is bound to displease some, perhaps severely. Pet views and favored findings will be found flouted, or worse, ignored. Offensive definitions and despised results will be viewed as excessively flaunted. Some chapters will be regarded as too verbose, and others as too skimpy. All these criticisms and others have transpired even in the valued comments of our own Technical Review Panel. Yet, the effort had to be undertaken, and the report had to be written. The test of its success will be its utility to those readers for whom it was designed.

The work described here was performed by Dr. Alex Hershaft with the assistance of Mr. G. Bradford Shea and Mr. John D. Morton, all of Enviro Control. Other contributors included Dr. James S. Whang of Enviro Control and Dr. Eugene P. Seskin of the National Bureau of Economic Research. Ms. Anita Calcote was responsible for typing and production of the report.

Critical review of the interim drafts and numerous valuable comments were provided by a distinguished Technical Review Panel composed of six recognized authorities on dose-effect functions, though the responsibility for any errors of omission or commission rests exclusively with the principal author. Their names, affiliations, and specialties are as follows:

- Dr. Robert W. Buechley, Statistical Epidemiologist, School of Medicine, University of New Mexico
  - Health effects of air pollutants

- Dr. Lester B. Lave, Head, Department of Economics, Carnegie-Mellon University
  - Health effects of air pollutants

- Dr. Carl M. Shy, Director, Institute for Environmental Studies, University of North Carolina
  - Health effects of air pollutants

- Dr. 0. Clifton Taylor, Associate Director, California Statewide Air Pollution Research Center
  - Effects of air pollutants on vegetation

- Dr. Warren Winkelstein, Dean, School of Public Health, University of California, Berkeley
  - Disease effects of air pollutants

- Mr. John E. Yocom, Vice President, The Research Corporation of New England
  - Effects of air pollutants on materials.

Finally, this entire effort would not have been possible, but for the foresight, initiative, and helpful guidance of Dr. James J. Reisa, the CEQ Project Officer. Dr. William C. Nelson of the U.S. EPA's National Environmental Research Center at Triangle Park, North Carolina, was the cognizant U.S. EPA Project Officer.

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EXECUTIVE SUMMARY

The discussion, analysis, and conclusions of this report are summarized here under the headings of introduction, survey of state of knowledge, analytical methodology,analysis of selected functions, and research needs.

A. INTRODUCTION

This section introduces the major concepts and issues underlying the subject matter of this report. The topics covered include the role and nature of dose-effect functions, nature and effect of air pollutants, and the purpose, objectives, scope, and organization of the report.

1. Overview

Damages associated with air pollution may take the form of increased mortality and incidence and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well identified losses. Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and secondary economic effects. Although benefit /cost analysis is not an exact science and the results are difficult to express in monetary terms, the inherent process of logical and systematic scrutiny can contribute substantially to the ability of decision makers. to allocate more efficiently the limited cleanup resources.

There exists an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. A damage, or dose-effect, function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated effect on a target population. In plotting such a function, the ordinate may represent either the number of individuals affected or severity of effect, whereas the abscissa indicates the dosage in terms of time and ambient concentration. In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population.

The data required to develop dose-effect functions may be obtained through epidemiological, field, clinical, toxicological, or laboratory investigations. The principal techniques for analyzing the relationship between exposure and effect indices in epidemiological and field studies are known as cross tabulation, multivariate regression, and distribution-free analysis. In employment of these techniques, it is important to isolate or control the influence of cofactors and covariates. Controlled experiments, such as toxicological and laboratory investigations, are used to test observations gained from epidemiological and field studies.

Dose-effect functions can serve as valuable instruments in the popular conceptualization of the threats posed by environmental pollution, in determination of an optimal extent of pollution abatement, and in development of a more rational allocation of limited resources. However, these functions suffer from some important drawbacks that diminish their usefulness. They are frequently based on insufficient data; they force a quantitative interpretation on relationships that cannot be validly quantified, and they fail to account properly for synergistic or antagonistic relationships.. The major problem areas are collection and retrieval of reliable ambient air quality data, selection of exposure indicators, selection of representative populations, determination of effects, establishment of causal relationships, and presentation of results.

2. Purpose and Scope

The purpose of this effort is to assess and demonstrate the utility and potential applications of existing and emerging air pollution dose-effect functions. The specific objectives are to assess the state of the art in developing air pollution dose effect functions, to interpret and communicate the significance of available and emerging functions, and to suggest improvements in analytical methodology and define new areas for study.

The effort was organized under five tasks presented in four chapters and an appendix, as set forth below:

- Prepare survey of literature on dose-effect functions (Chapter II)
- Prepare survey of methodology (Chapter III)

- Analyze selected dose effect functions (Chapter IV)
- Discuss future needs and projects (Chapter V)
- Prepare demonstration for CEQ annual report (Appendix).

The pollutants included in this study are total suspended particulates, sulfur dioxide, nitrogen dioxide, photochemical oxidants, carbon monoxide, hydrocarbons, sulfates, nitrates, and fluorides. Only physical and biological, as distinct from economic, effects are examined and both chronic and acute responses are considered. The effect categories encompass health effects, vegetation damage, materials damage, and such other effects as aesthetic impairment and climatic changes.

B. SURVEY OF STATE OF KNOWLEDGE

The effects of air pollutants have been addressed by numerous investigators during the past decade. However, many of these studies display limited applicability, insufficient concern for impact of covariates, or other flaws that frustrate aggregation of the results into a valid and meaningful dose-effect function. A number of selected studies are surveyed here under five categories of effects: human health, vegetation, materials, aesthetics and weather, and effects of water pollutants.

1. Effects on Human Health

Effects of air pollutants on human health have received the most attention because of their relatively high social importance. The most generally useful relationships between exposure to air pollutants and health effects have been obtained from epidemiological studies. Clinical and toxicological observations have not been included in the survey because of the difficulty of extrapolating their results to the general human population. Studies that do not formulate meaningful quantitative relationships, fail to control for relavant covariates, or merely report on catastrophic air pollution episodes have also been excluded.

The major pollutants investigated are sulfur oxides and particulates, nitrogen oxides, photochemical oxidants, carbon monoxide, and unspecified air pollutants. The princpal effects are mortality and morbidity, but each of these may be further characterized by specific diseases, such as respiratory and cardiovascular dysfunctions, neoplasms of the respiratory and gastrointestinal tracts, chronic nephritis, and impaired fetal development and mental function. Indicators of morbidity include absenteeism, hospital admissions and residence days, doctors' visits, and personal histories.

A number of important cross-sectional epidemiological studies have compared the effects of sulfur oxides and particulates on populations of various metropolitan areas. The effects of nitrogen oxides on human health have received relatively less attention, perhaps because of the difficulty of measuring ambient concentrations and the lack of reliable historical data. Only two studies of the effects of photochemical oxidants on human health

were found to meet all of the selection criteria. Effects of carbon monoxide on human health have been investigated almost entirely by toxicological experiments and clinical observations in conjunction with occupational exposure. Finally, several useful investigations were conducted on the effects of other pollutants or non-specific air pollution.

2. Damage to Vegetation

Concern for air pollution damage to vegetation has received renewed impetus from the recent discovery of heretofore unsuspected high oxidant levels in rural areas and the completion of investigations indicating substantial crop losses at these levels. In the past, there had been relatively little interest in coordinating the efforts of various investigators or in setting uniform standards and conditions that would permit some aggregation or comparison of the results of different studies.

The principal pollutants implicated in substantial damage to vegetation are sulfur dioxide, oxidants, nitrogen oxides, acid rain, and fluorides. Determination of effects on craps and forests is severely handicapped by the virtual lack of monitoring stations in rural areas. Effects of air pollutants on vegetation exhibit wide variations among the various species and as a result of different genetic and environmental conditions. The latter includes stage of growth, general viability and vigor, temperature, humidity, amount of insolation, soil moisture and acidity, and availability of nutrients. In the past, determination of effects was based largely on measurement of the extent of leaf injury, but more recently, it has been realized that substantial yield losses can occur even in the absence of significant leaf injury.

The state of development of consistent and broadly applicable dose-effect functions in the area of vegetation damages is considerably less advanced than in the areas of health effects or material damages. The fault may be attributed to the scarcity of air quality records in rural areas, some lack of foresight and coordination in the design of investigations and presentation of results, but most of all to the broad variety of target species and the ensuing variability of effects.

Early studies identified sulfur dioxide as the primary factor in air pollution damage to vegetation, but more recent investigations have examined the effects of acid rain and mist. Effects of photochemical oxidants, including ozone, have attracted a great deal of attention in the wake of the recent discovery of high oxidant levels in rural areas. Investigations of the effects of nitrogen oxides have suffered from difficulties of measurement, rapid fluctuations of ambient levels due to chemical reactions, and the synergistic effects with sulfur dioxide and oxidants.

3. Damage to Materials

Investigation of the effects of air pollutants on materials permits the control of both exposure and the make-up of the target population. Nevertheless, useful dose-effect functions in this area are largely confined to representations of the corrosion of metals by sulfur oxides and the soiling of exposed surfaces by particulates. Other pollutants studied include particulates, nitrogen oxides, and oxidants. Other target populations are paper, textiles, leather, paints and dyes, rubber, plastics, metals, ceramics, and stone.

Effects of long-term exposures have been determined by exposing test panels to ambient conditions for long periods of time. The results of these field studies have been flawed by poor ambient level measurements and failure to account for other pertinent environmental variables. Laboratory studies have attempted to determine short-term effects by subjecting test panels to elevated pollutant concentrations. Recent laboratory experiments have used more realistic concentrations.

4. Other Effects of Air Pollution

Other effects of air pollutants include aesthetic and meteorological effects. Aesthetic effects may take the form of reduced visibility or offensive odors. Meteorological effects involve changes in precipitation patterns and in the mean temperature of the earth's atmosphere. Aesthetic effects have been measured in monetary terms by assessing the people's willingness to pay for pollution control leading to a reduction of the offensive condition.

5. Effects of Water Pollution

Effects of water pollution have received less quantitative scrutiny than effects of air pollution, perhaps because loss of recreation, the largest effect, is too difficult to measure, and because most effects are attributable to different combinations and concentrations of various pollutants. Dose-effect functions have been developed for the effects of various pollutants on fish and other aquatic organisms, as well as on household plumbing fixtures.

C. ANALYTICAL METHODOLOGY

In spite of the potential importance of dose-effect functions and the amount of effort that has gone into generating the necessary data, the methodology for developing these functions and handling of the attendant problems and uncertainties are still in their infancy. This section traces the methodology through the progressive stages of study design measurement of ambient levels, determination of exposure, determination of effect, estimation of functional relationships, and presentation of results.

1. Design of Study

Design of the study is a crucial stage in the dose-effect development process, for it sets the pattern for much of the subsequent effort and determines the usefulness of the results. The major decisions involve selection of pollutants and measures, effect and measures, population at risk, time frame and geographic area, and type of study.

Selection of pollutant typically requires also some attention to pollutants that may be acting synergistically or antagonistically toward the pollutant of interest. Selection of measures involves not only the specific units of measurement, but also the type of measures (averages or peaks) and periods of measurement.

Similarly, selection of effect entails decisions on types of effect, and units and periods of measurement. Selection of population at risk, geographic area, and time frame are usually governed by availability of data and funds, in addition to the usual criterion of intended use.

Characterization of the human population at risk is usually limited to sex, race, and age, because other personal and socio-economic traits are more difficult to determine and they fragment the size of the sample. In the case of vegetation and materials, characterization of the population at risk takes the form of specification of the plant species and precise material composition, respectively. The importance of these characterizations lies in their impact on the susceptibility or sensitivity of the population at risk to the effects under study.

In selecting the type of study, one must first choose the type of approach (i.e., epidemiological or field, clinical, toxicological or experimental, or survey). If the epidemiological or field approach is selected, additional decisions must be made on whether the study should be longitudinal (time-series) or cross-sectional (different communities) and retrospective or prospective, Personal surveys can provide amplification of health effects data and reporting of less tangible effects.

2. Determination of Ambient Levels

The principal problem areas in the determination of ambient air quality levels are collection of sufficient data, selection of optimal sampling modes and valid analytical techniques, averaging and aggregation of concentration levels over time and space, and determination of ambient levels in the immediate proximity of the subjects from measurements at monitoring stations.

Collection of sufficient air quality data to determine with some confidence the ambient levels of a community requires a large number of stations collecting frequent readings on several pollutants and a massive commitment to data handling well in excess of the present level. This is the case, because the various point, line, and area sources discharge intermittently into a fluid medium, where the pollutants undergo various transport, dilution, and chemical transformation processes.

Sampling mode is important if one is attempting to study acute effects of air pollution, which requires measurement of intensity and duration of concentration peaks, rather than daily or monthly averages. Valid analytical techniques are those that are specific for the pollutant under study and reasonably accurate. The data must be sufficiently disaggregated over time and space to serve the design requirements of the study.

3. Determination of Exposure

Exposure is typically measured as some formulation of ambient concentration levels and their duration which may be expressed as "dosage" (integral of the ambient concentration and its duration as recorded at the

monitoring station) or "dose" (that portion of dosage instrumental in producing the observed effect). The difference between these two quantities may be accounted for by non-uniformity of the pollution field, mobility of subjects, shielding of subjects, and uptake characteristics. An important concept in the determination of exposure is the dose rate, or the variation of concentration level with time.

Exposure of stationary subjects, i.e., plants and most materials, is determined by the dynamics of the pollution field alone. However, for humans, animals, and other moving subjects, exposure is governed also by their own mobility. The need to consider the effect of shielding by building enclosures is underlined by the fact that an overwhelming portion of the U.S. population spends some 85 percent of its life indoors. Humans and animals, termed "active" receptors, take up pollutants through inhalation and swallowing, whereas uptake by plants and stationary material objects, the "passive" receptors, is governed more by meteorological conditions, position of the affected surface, and the presence of any protective mechanisms.

The most common measures of exposure are average concentration during a given period of time or the amount of time at a given level of ambient concentration. Other common measures include the frequency, duration, and/or intensity of peaks or instances when ambient concentration exceeds a certain level, as well as dosage, i.e., the integral of concentration and time. The construction of composite indices, made up of several measures of exposure, has been suggested. Measurements of the actual dose are not generally feasible, nor necessarily useful, because the difference between dose and the measure employed becomes implicit both in the development and the interpretation of the dose-effect function.

4. Determination of Effect

The effect of air pollutants on a given target population is defined in terms of the type of effect, its duration, reversibility, sensitivity of the target population, specificity, threshold and saturation, and measures of effect. Terms commonly used to denote effect include

response, injury, and damage. Duration of damages provides for their classification as chronic or acute. Reversibility refers to the ability of the subject to repair the damage and restore the function upon cessation of exposure.

The type and severity of effects are governed in large measure by the sensitivity and susceptibility of individual members or classes of the target population. In assessing specific effects, it is very important to isolate the influence of any cofactors (factors that act simultaneously, synergistically, or antaganistically with the pollutants), and mimics (factors that simulate the effect of certain pollutants).

The effects of air pollutants on human health may be classified as body burden, uncertain physiological changes, adverse physiological changes, morbidity, and mortality. Morbidity, including the incidence and prevalence of disorders, and mortality are by far the most commonly investigated types of health effects. In most cases, the data are broken down by specific disorder and by characteristics of the target population.

Effects of air pollutants on vegetation are manifested through physiological changes, various types of injury to leaves and other parts of the plant, reduced yield, reduced plant growth, and death. The most remarkable feature of past measurements of air pollutant effects on vegetation is their wide diversity which frustrates attempts at verifying, comparing, or aggregating the results of different studies. The major cofactors in effect of air pollutants on vegetation are the meteorological conditions, such as humidity, precipitation, insolation, temperature, and air turbulence, as well as soil moisture and nutrient content,

Effects of air pollutants on materials are rather well defined in comparison with health or vegetation effects, because of greater uniformity of samples, simpler damage mechanisms, and higher reproducibility of results. The principal effects may be classified as soiling and coating of exposed surfaces, corrosion of metals, degradation of textiles, rubber, and masonry surfaces, and fading of dyes. The important cofactors affecting the attack of materials include humidity, temperature, sunlight, and air turbulence.

5. Estimation of Functional Relationship

The more common statistical techniques for defining the quantitative relationship between exposure and effect are cross tabulations or simple correlations, multivariate regression analysis,and distribution-free analysis. The difficulty with the first method is that a host of other factors are allowed to vary across populations, so that it is usually not feasible to isolate the effect of pollutants alone. Multivariate regression analysis permits statistical control over interfering factors and provides a rapid estimate of the degree of association between a number of independent variables and the dependent variable. Distribution free analysis requires fewer assumptions about the distribution of the variables, but its use is more time consuming and requires greater intervention of human judgment.

The principal covariates in air pollution effect studies are other pollutants, other types of exposure, meteorological conditions, personal and socio-economic characteristics. of the target population, and timing. An ideal investigation of the specific effects of an air pollutant would hold constant, or control all likely covariates. This can be accomplished, respectively, by judicious design of the investigation, or by statistical techniques.

6. Presentation of Results

The classical representation of the relationship between exposure and effect takes the form of a sigmoid, or S-shaped curve. The ordinate may represent either the number of individuals affected or severity of effect, whereas the abscissa indicates the dosage, in terms of time at the given ambient concentration, or ambient concentration over a fixed period of time. Nearly all dose-effect functions reviewed in this study represent some variation on this basic relationship.

The most general type of relationship between exposure and effect is "associative", meaning that certain effects have been found associated with given levels of exposure. Establishment of the more rigorous "causal"

relationship requires the inducement of direct or indirect evidence of causation. Evidentiary characteristics of a causal relationship include strength, specificity, and consistency.

The measures of exposure and effects are characterized by a unit of measurement, a specific pollutant, a given effect, an instant or interval of time, a geographic location, and a target population. The results of dose-effect studies are reported in terms of some combinations of the various levels of aggregation of these parameters.

Errors in representing dose-effect functions may be characterized as errors of specification and measurement. A particularly common and grave error of specification is committed in attempting to extrapolate a complete functional relationship from a few data points. Errors of measurement may be incurred in the course of measuring ambient levels, exposure, and effects. They may be represented graphically as an envelope about the plot of the dose-effect function. Such envelopes may be derived through replication of a specific investigation using new data, manipulation of values of the more important variables, combining results of several studies, applying "best" and "worst" case assumptions, and bounding available data points.

D. ANALYSIS OF SELECTED FUNCTIONS

This section provides an in-depth analysis of selected dose-effect functions to determine improvement in their validity and applicability. The presentation begins with selection of three functions and continues with an analysis based on the methodology discussed in the preceding section.

1. Selection of Functions

The impact of a dose-effect function on potential policy decisions may be determined on the basis of importance of the effect, data quantity and compatibility, data quality, and validity of the function. The relative importance of these criteria to the selection process depends on the category of effects, specific objectives of the selection process, and the subjective considerations of the investigator.

In light of all these considerations, the following three dose-effect functions were selected for in-depth analysis:

- Sulfur dioxide (or sulfates) - human mortality
- Ozone - injury to tobacco leaves
- Sulfur dioxide (or sulfates) - corrosion of zinc.

2. Effect of Sulfur Dioxide on Human Mortality

Effects of sulfur dioxide on human mortality represent the most intensively studied area of air pollution effects. The specific dose-effect function selected here, was developed by Buechley, et al. as a significant predictor of daily mortality in a large, densely populated, highly polluted metropolitan area (the New York-New Jersey-Connecticut air quality control region).

Measurements of air quality for the entire area were based on readings from only one air pollution monitoring station, The specific measure of concentration was obtained by averaging hourly concentration

readings over each 24-hour period. The target population was the entire population of the area and the measure of effect was total mortality. The study emphasized acute, rather than chronic effects by looking at daily averages and failed to take into account individual differences in susceptibility among the various classes of population.

Multiple regression analysis was used to estimate the individual contributions of a number of variables to the mortality ratio. These included an annual cycle, extreme heat, influenza epidemics, warm and cold weather, holidays, day of the week, sulfur dioxide, and coefficient of haze, With the other covariates controlled, sulfur dioxide and coefficient of haze showed a significant correlation with the mortality, However, it is likely that these measures had acted as proxies for sulfates or some other species. This restricts the applicability of the dose-effect function to other locations, where distribution of pollutants may differ significantly.

The recommended actions are: more extensive monitoring of SO_2, sulfate, and particulate levels, collection of cause-specific mortality data, more detailed determinations of health effects of specific pollutants, and characterization of the target population.

3. Effects of Oxidants on Tobacco Leaves

Several investigators have characterized injury to tobacco leaves by oxidants and related. factors. The specific dose-effect function selected here was developed by Heck, et al. for the Bel W-3 cultivar of tobacco. The graph of the function provides a vivid demonstration of the different effects of the concentration and time elements of exposure on leaf injury, permitting the interpretation of both chronic and acute effects.

The plants were grown in controlled environment chambers approximating field conditions. Ozone levels were measured with a coulometric MAST recorder.

Leaf injury was manifested in the form of flecs, which make the leaf undesirable as cigar wrapper, and measured in terms of the fraction of leaf surface covered by the flecs. Other measures that have been suggested include reduction of leaf growth rate, photosynthesis, or stomatal conductance.

Validity of the specific dose-effect function presented should be rather good, because it is based on results of controlled experiments. The principal reservations are the uncertain relationship between ozone measurements and oxidant concentration, failure to isolate the effect of meteorological factors, artificial flattening of concentration fluctuations, and subjective measurement of damage. The function suggests that exposure of the more sensitive varieties of tobacco to levels permitted under the national air quality standard for photochemical oxidants may cause substantial damage.

The recommended actions are: establishment of guidelines and criteria for conducting research on affects of air pollutants on vegetation, collection of more complete data on oxidant levels in rural areas, development of more precise and appropriate damage measurement techniques, and definition of the synergistic effects of pollutants.

4. Effect of Sulfur Dioxide on Corrosion of Zinc

The dose-effect function selected was developed by Haynie and Upham from results of a series of controlled experiments in eight series over a period of up to 64 months. It expresses a linear relationship between an atmospheric factor composed of SO_2 concentration and relative humidity on one hand, and corrosion rate of zinc, on the other. The authors conclude that SO_2 is a major cause of zinc corrosion and that a relative humidity in excess of 49 percent is required before SO_2 attack can become effective.

Panels of high-grade zinc sheet were exposed to ambient air for five different periods of time. SO_2 ambient concentration data were obtained from nearby monitoring stations. Extent of corrosion was measured by cleaning the panels to remove corrosion products and determining the weight loss.

The analytical relationship developed accounts for 92 percent of the variability of average corrosion rates and yields an r value of 0.96. The general range of the data spans both the national standard and prevalent ambient values, permitting interpolation of most data of value. The major errors are associated with SO_2 measurement and relationships between dose values and ambient levels at the exposure sites.

The only actions recommended are characterization of errors in measurement of SO_2 levels and performance of a less extensive series of tests on zinc-coated steel in parallel with zinc sheet to determine relative corrosion rates.

E. RESEARCH NEEDS

This final section delineates a limited number of suggestions for additional research that were culled from the material presented in the preceding sections. These suggestions pertain exclusively to development of dose-effect functions and do not deal with such other related and interesting topics as improvement in air quality monitoring and modeling techniques or better understanding of effect mechanisms. Successive subsections address methodological improvements in determination of exposure and effect and additional dose-effect studies.

1. Determination of Exposure

The following research needs are suggested:

- Determine how well air quality measurements at the monitoring station represent the ambient quality in the surrounding community
- Determine the impact of mobility and shielding of the subjects on their exposure
- Develop a composite index of exposure
- Explore the possibility of translating different measures of exposure
- Define current air quality monitoring requirements for potential future dose-effect studies.

2. Determination of Effect

The following research needs are suggested in this area:

- Assess and improve the accuracy and reliability of the various methods for determining morbidity in dose-effect studies
- Develop a method for determining changes in life expectancy due to exposure to air pollutants
- Provide uniform guidance for designing studies of the effects of air pollutants on vegetation.

3. Study Design

Recommended research projects in the area of study design are:

- Assess the relative cost-effectiveness of Lave's "dream study" and a corresponding conventional epidemiological study
- Prepare a manual for developing dose-effect functions.

4. Additional Dose-Effect Studies

The following additional dose-effect studies are recommended:

- Specific effects of NO_2 and nitrates
- Specific effects of different types of sulfates
- Chronic effects of low-level exposures to various pollutants
- Carcinogenic, teratogenic, and mutagenic effects of air pollutants
- Effect of oxidants on yields of major crops
- Synergistic effects of sulfur oxide and oxidants
- Long-term effect of pollutants on ecological balance
- Effects on paints, cement, rubber, plastics, and wood
- Effects on aesthetic appreciation of an area, including visibility
- Effects on climate and local weather conditions.

CHAPTER I. INTRODUCTION

This chapter introduces the major concepts and issues underlying the subject matter of this study. The topics covered include the role and nature of dose-effect functions, nature and effects of air pollutants, and the purpose, objectives, scope, and organization of the study report.

A. OVERVIEW

Dose-effect, or damage functions constitute an important link in the cycle between environmental pollution, resultant damages, and pollution control measures. This section explores the role and characteristics of these functions, as well as the nature and effects of the pollutants investigated.

1. Environmental Damages and Benefits

Nearly everyone is now convinced that there exists a causal relationship between environmental pollution levels and certain damages suffered by society. These may take the form of increased mortality, increased incidence and prevalence of disease, diminished enjoyment of the outdoors, reduced crop yields, more frequent maintenance and replacement of exposed materials, and other, less well-identified losses. This being the case, a reduction in pollution levels would bring about a corresponding decrease in these damages and produce a set of benefits equivalent to the difference in damages before and after the reduction took place,. If the damages are reduced to the point at which they are no longer observed, then the benefits realized are equal to observed damages.

Legislators, planning officials, and other environmental decision makers are frequently faced with the decision of how much to reduce pollutant levels in the light of the associated direct costs of pollution control and possible secondary economic effects. In the past, these decisions were rather obvious and they were made in response to popular sentiment. However, with the passing of time, these costs became more acutely felt, especially in the wake of the energy crisis, while the beneficial effects of reduced, or at least stable, pollution levels were neither obvious nor easily measured. Clearly, the decision

makers would need a more sensitive tool for comparing and trading off the costs and benefits of various levels and types of pollution control. It was this need that gave birth to the science of environmental benefit/cost analysis.

Admittedly, benefit/cost analysis is not an exact science, primarily because social benefits and costs are diffuse and frequently difficult to express in monetary terms. Even so, the process of logical and systematic scrutiny inherent in benefit/cost analysis can contribute substantially to the ability of decision makers to improve the social welfare through more efficient allocation of the limited resources of the public treasury.

This potential contribution was recognized by the framers of the National Environmental Policy Act of 1969 (PL 91-190), primarily in Sections 102 and 204. Section 702 calls for the "identification and development of methods and procedures which will ensure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making, along with economic and technical considerations." Section 204 charges the Council on Environmental Quality to gather, analyze, and interpret timely and authoritative information concerning the conditions and trends in the quality of the environment.

2. Nature of Damage Functions

There exists an interactive relationship among pollutant emissions, ambient air quality, damages and benefits, and policy decisions. This is illustrated in the diagram in Figure 1, where rectangles indicate processes and actions, and ellipses represent their products. The pollutants emitted by stacks, automobile exhaust pipes, and other sources undergo physical and chemical interaction in the atmosphere under the influence of meteorological factors to yield prevailing ambient pollutant levels. The resulting physical or biological damages are converted into some realistic economic terms and traded off against the costs of controls to guide decision makers on the extent and type of controls to be applied. Alternatively, economic damages can be determined directly as a function of ambient levels through surveys of property values, declared willingness to pay, legislative decisions, and litigation awards.

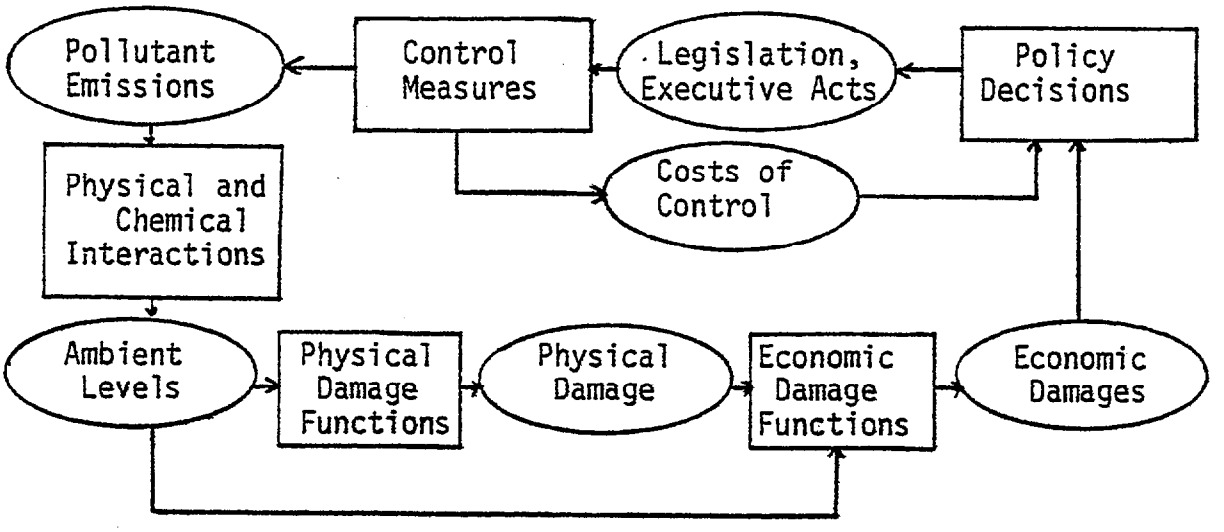


Figure 1. Cyclic Relationship Among Pollution-Related Activities and Their Products

A damage function represents the crucial link between ambient pollution levels and the resultant physical, biological, and/or economic damages. More specifically, a damage function is the quantitative expression of a relationship between exposure to specific pollutants and the type and extent of the associated damage to a target population. Exposure is typically measured in terms of ambient concentration levels and their duration and it may be expressed as "dosage" or "dose". Dosage is the integral of the time and ambient concentration to which the subject has been exposed, while dose represents that portion of the dosage that has been instrumental in producing the observed damage (e.g., the amount of pollutants actually inhaled in the case of health effects of air pollution).

The damage can become manifest in a number of ways and can be expressed in either physical and biological, or economic terms. If the effect is physical or biological, the resultant relationship is known as a physical or biological damage function, or a dose-effect function. In an economic damage function, on the other hand, the effect is expressed in monetary terms. Economic damage functions can be developed by assigning dollar values to the effects of a physical or biological damage function, or by direct correlation of economic damages with ambient pollutant levels.

In reporting a damage function, one needs to specify the pollutant, the dose rate, the effect, and the target population, or the "population at risk". Dose rate, or the rate at which ambient concentration varies with time, has a major influence on the nature and severity of the resultant effect. Long-term exposure to relatively low concentrations of air pollutants may result in manifestations of chronic disease, characterized by extended duration of development, delayed detection, and long prevalence. Short-term exposure to high concentration levels, on the other hand, may produce acute symptoms, characterized by quick response and ready detection, as well as chronic, cumulative, or delayed effects.

Specification of the population at risk involves the characterization of the nature and magnitude of the exposed population. It is crucial to this exercise for several reasons. First, it serves to define the total damages produced by a given level of exposure by multiplying the corresponding unit damage (e.g., increased mortality) for the specified population at risk (e.g., white males over 65) by the total number of units within this population. Secondly, it permits investigators to adjust their results to reflect the influence of various intrinsic (e.g., age, race, sex) and extrinsic (e.g., general health, occupation, income and education) variables in assessing the specific effects of air pollutants (e.g., increased incidence of lung cancer). Finally, it can provide useful guidance for allocating air pollution control resources by identifying areas with particularly susceptible populations exposed to relatively hazardous levels of pollutants.

A typical sigmoid, or S-shaped damage function, showing the damage corresponding to a given exposure to a specific air pollutant, is presented in Figure 2. The ordinate may represent either the number of individuals affected or severity of effect. The abscissa indicates the dosage in terms of time at a given ambient concentration, or in terms of ambient concentration for a fixed period of time. The lower portion of the curve suggests that, up to a certain exposure value, known as a threshold level, no damage is observed, while the upper portion indicates that there exists a damage saturation level (e.g., death of the target population or total destruction of the crops), beyond which increased

exposure levels do not produce additional damage. The middle, quasi-linear portion is very useful in that any data points here can be readily interpolated, and the frequent assumption about linearity of a damage function is most valid in this sector.

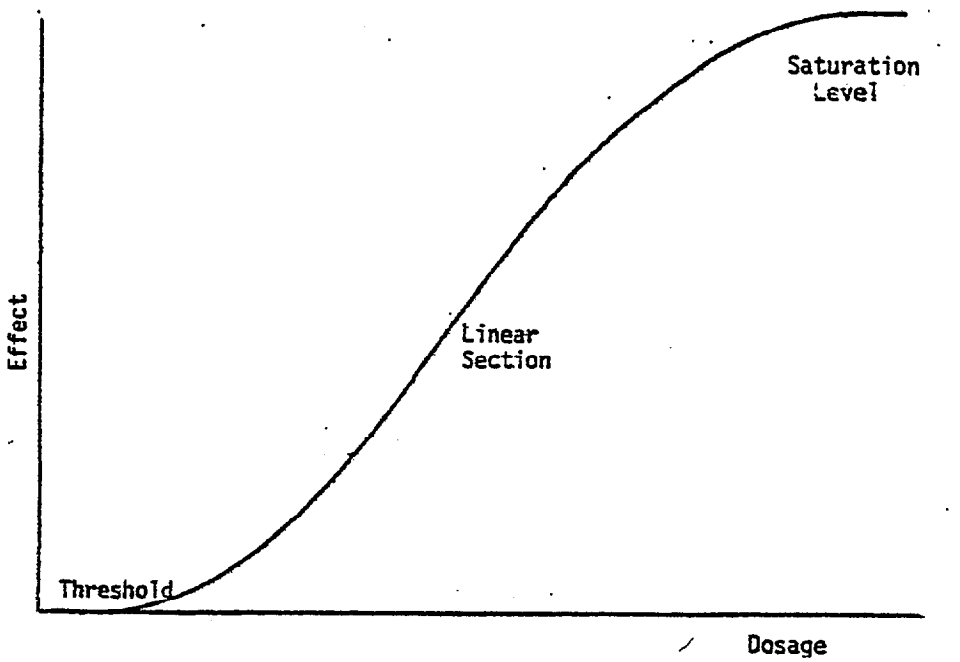


Figure 2. Hypothetical Dose-Effect Function

3. Development of Dose-Effect Functions

The data required to develop physical or biological damage functions are obtained primarily through epidemiological, field, clinical, toxicological , or laboratory investigations. The first approach involves the comparative examination of the effects of pollutants on selected segments of population exposed to different levels of pollution, in order to deduce the nature and magnitude of the likely effect. Field observations represent a similar approach to assessment of effects on animals, vegetation, and materials, and they are characterized by similar analytical techniques and concerns. Clinical studies are based on hospital observation of the results of exposure on human subjects. Toxicological investigations involve deliberate administration of controlled doses of pollutants to animal, and occasionally, human subjects, and observation of the resulting effects. Laboratory studies represent essentially the same approach for determining effects of pollutants on plants and materials.

The three principal techniques for analyzing the relationship between exposure and effect indices in epidemiological and field studies to construct a damage function are known as cross tabulation, multivariate regression, and non-parametric or distribution-free analysis. Cross tabulation is the simplest of the three. Multivariate regression provides a rapid indication of the degree of association between a large number of independent and the dependent variables and is readily programmable for computer operation. However, its validity is heavily contingent on a fairly precise a priori definition of the relationship between each independent and the dependent variables and on precise measurement of the independent variables. Thus, this technique is especially vulnerable to the poor precision in measurement and reporting of air pollution levels for a given segment of population. Non-parametric analysis, on the other hand, is free of these assumptions, but requires laborious data reduction for each of the many pairs of independent and dependent variables and expert judgment to guide each step of the process.

In the development of dose-effect functions on the basis of epidemiological or field studies, it is important to isolate or control the influence of cofactors and covariates. The former may be defined as factors that act in concert with the independent variables (e.g., relative humidity or cigarette smoking and pollutant level). Covariates, on the other hand, may be thought of as factors that vary jointly with the principal variable. The distinction between cofactors and covariates is not well defined, nor terribly useful or important.. Their interference with results of the analysis can be reduced by holding them constant or with the aid of statistical techniques. When this cannot be done, it is frequently assumed that the distribution of these factors in the target population is sufficiently uniform to avoid vitiating the basic conclusions.

Finally, it should be noted that epidemiological and field studies and observations can only indicate an association between exposure to pollution and the observed effect, suggesting the existence of a causative relationship. Such a relationship can then be tested by toxicological and laboratory studies, or rendered plausible by the presentation of a plausible connective mechanism, or other weight of reason.

4. Merits and Drawbacks

As was noted earlier, dose-effect functions constitute an important link in the interactive relationship between pollutant emissions, resultant damages, and pollution control measures. Accordingly, they can serve as valuable instruments in reaching the following intermediate objectives in our social decision-making process:

- Popular conceptualization of the threats posed by environmental pollution and the beneficial changes wrought by abatement
- Determination of an optimal extent of pollution abatement through a cost-benefit tradeoff analysis
- Development of a more rational allocation of limited resources in improving environmental quality and other aspects of public welfare.

Despite these unquestioned conceptual merits, the development and application of dose-effect functions has been subjected to a great deal of critical commentary, much of it justified. The more cogent of these comments are listed below:

- Dose-effect functions are frequently based on insufficient data, requiring daring extrapolations of a curvilinear function from too few data points
- They attempt to represent complex and dynamic relationships by quasi-linear and static functions
- They force a quantitative interpretation on certain relationships that cannot be validly quantified
- They fail to account property for synergistic or antagonistic relationships.

In fact, development of air pollution dose-effect functions is beset by a number of major difficulties that compromise their accuracy and reliability. Some of these difficulties can be readily overcome with the aid of available ancillary information, while others require the expenditure of much additional effort. The more important problem areas may be listed as follows:

- Collection and retrieval of reliable ambient air quality data
- Selection of exposure indicators
- Selection of representative populations
- Determination of effects
- Establishment of causal relationships
- Presentation of results.

Currently available air quality data do not represent well average ambient concentrations, and seldom reflect hourly, or even diurnal variations. Generation of more reliable and complete data would require a drastic expansion of current monitoring networks and a commitment to massive data handling or the development and application of substantially improved computer models for simulating atmospheric processes. Then there is the problem of selecting the proper exposure indicator for each pollutant, in terms of level, duration, and presence of other pollutants, or cofactors.

Another problem is the need to select sample populations that are representative of the population at large in terms of susceptibility to detectable levels of damage. In the case of health effects, this involves selection based on demographic and socio-economic makeup of the population at risk. Determination of effects involves choice of a useful effect indicator and differentiation from similar effects due to other factors. Perhaps the most formidable problem lies in identifying and documenting a plausible causal relationship, or at least a strong association between exposure to a given dose and observation of a specific effect and in deriving the corresponding damage function. Unfortunately, many damage functions are based on only a few discrete points, and require heroic assumptions about their shape.

All of these problems and others deserve much attention, because of the vast potential benefits to be derived from their solution. The state of the art of developing dose-effect functions, additional benefits to be extracted from current state of knowledge, and the more urgent problems to be addressed in the near future need to be explored in some depth. This is what this study hopes to accomplish.

B. PURPOSE AND SCOPE

This section delineates the general purpose, specific objectives, scope, and organization of this study, within the setting laid down in the preceding section.

1. Purpose and Scope

The purpose of this effort is to assess and demonstrate the utility and potential applications of existing and emerging physical air pollution damage (dose-effect) functions. The specific objectives designed to carry out this purpose are as follows:

- To assess the state of the art in developing air pollution dose-effect functions
- To interpret and communicate the significance of available and emerging damage functions
- To suggest improvements in analytical methodology and define new areas for study in furtherance of these objectives.

The effort was organized under five tasks presented in four chapters and an appendix, as set forth below:

- Prepare survey of literature on dose-effect functions (Chapter II)
- Prepare demonstration for the CEQ Annual Report (Appendix)
- Analyze selected dose-effect functions (Chapter IV)
- Prepare survey of methodology (Chapter III)
- Discuss future needs and projects (Chapter V).

The literature survey describes and evaluates the present state of knowledge regarding the development and uses of damage functions and provides the basis for selecting several damage functions for subsequent in-depth analysis. The brief demonstration for the CEQ Annual Report is

designed to show how air pollution damage functions can serve as interpretive aids in communicating the significance of air quality trends to persons who lack technical training. The analysis of selected dose-effect functions is designed to enhance the scientific validity and usefulness of these functions. The methodology survey describes and evaluates the various analytical approaches and techniques used in the interpretation of data and in the construction and application of air pollution damage functions. Finally, the last task addresses the more important needs for further study, research, data collection, and other development.

The scope of this effort can be defined in terms of pollutants, effects, and effect categories. These items are spelled out in Table 1 for air pollutants and discussed briefly below. Water pollutants are considered only in those selected cases where a significant damage function has been developed. Only physical and biological, as distinct from economic, effects are examined and both chronic and acute responses are considered. The effect categories encompass health effects, damage to vegetation, damage to materials, and other effects, such as visual impairment or climatic changes.

2. Pollutants Studied

The air pollutants included in this study are identified in Table 1. The term "particulates" refers to a wide variety of solid and liquid airborne particles introduced by a number of human and natural activities. The effects of certain specific particulates, such as sulfates, nitrates, and fluorides, are covered elsewhere, but even inert particles tend to aggravate the effect of gaseous pollutants. Particulates are also responsible for the soiling of building materials and other exposed surfaces, as well as impaired visibility.

Sulfur dioxide is formed by oxidation of sulfur, primarily during combustion of sulfur-bearing substances, such as coal or oil, but also in industrial processes. In combination with particulates, moisture, and/or oxidants, it forms acid sulfates which are very damaging to human health, vegetation, and materials. Health effects associated with sulfur

Table 1. Characteristics and Effects of Major Air Pollutants

Pollutant	Characteristics	Principal Sources	Health Effects	Other Effects
Total Suspended Particulates* (dust, pollen, ash, soot, metals)	Any liquid or solid matter dispersed in the atmosphere	Natural processes (e.g., volcanic eruptions, wind erosion, forest fires, atmospheric reactions); stationary combustion (especially of solid fuels); construction activities; industrial processes	Some direct effects, but primarily aggravation of the effects of gaseous pollutants	Interference with photosynthesis of plants. Soiling and deterioration of building materials, electric contacts, and other exposed surfaces. Impaired visibility and insolation; cloud formation.
Sulfur Dioxide * (SO_2)	A colorless gas with pungent odor	Combustion of sulfur-containing fuels; smelting of sulfur-bearing metal ores; industrial processes; natural processes (e.g., volcanic eruptions, atmospheric reactions)	Aggravation of respiratory diseases, including asthma, chronic bronchitis, emphysema; reduced lung function; irritation of eyes and respiratory tract; suspected contribution to respiratory and gastro-intestinal neoplasms	Leaf injury and reduced growth in plants. Corrosion of metal; deterioration of paper, textiles, leather finishes and coatings, building stone. Formation of acid rain; impaired visibility.
Nitrogen Dioxide * (NO_2)	A brownish-red gas with pungent odor	Motor vehicle exhaust; high temperature combustion; atmospheric reactions	Aggravation of respiratory diseases; suspected contribution to cardiovascular disease, respiratory neoplasm, and chronic nephritis; suspected increase in susceptibility to infection	Reduced growth and premature leaf drop in plants. Fading of dyes. Disruption of atmospheric ozone layer; impaired visibility.
Photochemical Oxidants* (O_3, PAN, aldehydes, other)	Colorless gaseous compounds; powerful oxidizing agents; principal components of photochemical smog	Atmospheric reactions	Aggravation of respiratory and cardiovascular diseases; reduced lung function; irritation of eyes and respiratory tract; suspected contribution to respiratory neoplasm and impaired fetal development	Leaf injury, reduced growth, and premature leaf and fruit drop in plants. Deterioration of rubber products; fading of dyes. Impaired visibility.
Carbon Monoxide* (CO)	A colorless, odorless, tasteless gas; has high affinity for hemoglobin in the blood	Motor vehicle exhaust; incomplete combustion of carbonaceous substances; natural processes (e.g., forest fires, decomposition of organic matter)	Reducted tolerance for exercise; impaired mental activity; impaired fetal development; aggravation of cardiovascular diseases	Not known.
Hydrocarbons * (HC)	Compounds of hydrogen and carbon in gaseous (e.g., methane, ethylene, acetylene) or particulate (benzo-a-pyrene) form	Motor vehicle exhaust, incomplete combustion of carbonaceous substances; processing, distribution, and use of petroleum compounds; natural processes (e.g., forest fires, metabolic processes of plants, atmospheric reactions)	Suspected contribution to neoplasms by benzo-a-pyrene	Major ingredient in the formation of oxidants through atmospheric reactions.
Sulfates ($SO_4^=$)	Corrosive aerosol in the form of sulfuric acid (H_2SO_4) mist or rain	Oxidation of sulfur dioxide in the atmosphere in the presence of moisture	See sulfur dioxide	See sulfur dioxide for plants. Damage to electric contacts. Acidification of soil and surface waters.
Nitrates (NO_3^-)	Corrosive aerosol in the form of nitric acid (HNO_3) mist or rain	Oxidation of nitrogen dioxide in the atmosphere in the presence of moisture	See nitrogen dioxide	See nitrogen dioxide for plants and materials. Acidification of soil and surface waters.
Fluorides (F^-)	Gaseous and solid compounds of fluorine	Industrial processes (e.g., production of phosphate fertilizer, aluminum metal, brick, and tile); combustion of coal	Irritation of respiratory tract and other sensitive tissues; inhibition of enzyme action	Leaf injury and reduced growth in plants. Corrosion of metals, damage to ceramics. Deposition in soil and accumulation in crops.

(*) Pollutants for which national environmental standards have been promulgated.

oxides include aggravation of respiratory diseases, such as asthma, chronic bronchitis, and emphysema, reduced lung function, irritation of eyes and respiratory tract, and suspected contribution to respiratory and gastrointestinal neoplasms. Vegetation suffers from leaf injury and reduced growth. Materials effects take the form of corrosion of metals, deterioration of textiles, paper, leather, finishes and coatings, and building stone.

Nitric oxide (NO) and some nitrogen dioxide (NO_2) is formed by reaction of oxygen and nitrogen during high temperature combustion, such as occurs in automobile engines. Nitric oxide reacts with oxygen in the atmosphere, especially in the presence of photochemical oxidants, to form nitrogen dioxide, which then undergoes additional complex reactions with ozone and hydrocarbons under the influence of UV radiation to produce the familiar smog. Nitrogen dioxide is an acute irritant responsible for a number of health effects, such as aggravation of respiratory diseases and suspected contribution to cardiovascular diseases, respiratory neoplasm, and chronic nephritis. It has been also implicated in reduced growth and premature leaf drop of plants and in the fading of dyes. Investigations of the effect of nitrogen dioxide has been greatly handicapped by its numerous atmospheric reactions, the resultant rapid fluctuation of its ambient concentration, and the lack of an acceptable measurement technique.

Photochemical oxidants, referred to incorrectly as smog, are formed by a series of complex atmospheric reactions from hydrocarbons and the nitrogen oxides. Their chief constituents are ozone (O_3) and peroxyacetyl nitrate (PAN), as well as a number of other organic compounds. Oxidants have been held responsible for aggravation of respiratory and cardiovascular diseases, reduced lung function, irritation of eyes and respiratory tract, and suspected contribution to respiratory neoplasm and impaired fetal development. Effects on vegetation and materials include leaf injury, reduced plant growth, premature leaf and fruit drop, deterioration of rubber and textile products, and fading of paints and dyes.

Carbon monoxide and hydrocarbons are formed by the incomplete combustion of organic fuels, such as occurs in automobile engines. Carbon monoxide has been implicated in reduced tolerance for exercise, impaired mental activity, impaired fetal development, and aggravation of cardiovascular diseases. The major impact of hydrocarbons lies in the formation of photochemical oxidants.

Acid rain is formed by scavenging of sulfuric and nitric acid mist by raindrops. The effects of acid rain on plants and materials resemble those of sulfur oxides. In addition, acid rain contributes to the acidification of surface waters and soil, which is detrimental to plant growth and to various uses of water.

Fluorides are formed by source industrial processes, including the production of aluminum, steel, ceramics, and phosphate fertilizer, and therefore, they represent a localized pollution problem. Although the health and material effects of fluorides have not been adequately investigated, these compounds are known to produce foliar injury and reduced growth in plants. They can also affect adversely animals foraging on these plants.

II. SURVEY OF STATE OF KNOWLEDGE

The effects of air pollutants have been addressed by numerous investigators during the past decade. However, many of these studies display limited applicability, insufficient concern for impact of covariates, or other flaws that frustrate aggregation of their results into a valid and meaningful dose-effect function. A number of selected studies are surveyed here for five categories of effects: human health, vegetation, materials, aesthetics and weather, and effects of water pollutants.

A. EFFECTS ON HUMAN HEALTH

Effects of air pollutants on human health have received the most attention because of their relatively high social importance. Studies of these effects are reviewed here for each of the major pollutants: sulfur oxides and particulates, nitrogen oxides, photochemical oxidants, carbon monoxide, and non-specific-air pollution.

1. General Remarks

The most generally useful relationships between exposure to air pollutants and health effects have been obtained from epidemiological studies, which compare observed effects on selected target populations with exposure as a function of location or time. Clinical and toxicological observations, based on controlled experience with human and animal subjects, have been excluded, because of the difficulty of extrapolating their results to the general human population. Studies that do not formulate meaningful quantitative relationships, fail to control for relevant covariates, or merely report on catastrophic air pollution episodes have also been excluded here, because they do not contribute substantially to the development of dose-effect functions. Nevertheless, inclusion or exclusion of a specific investigation in this listing is not necessarily a reflection on the quality of work or validity of the results.

A summary listing of the investigations reviewed here is provided in Table 2, which specifies the pollutant, major covariates, target population, effects, and author reference. The major pollutants

Table 2. Selected Studies of Health Effects of Major Air Pollutants

Pollutants	Target Population	Covariates	Results	Reference
Particulates, sulfates	U.S. SMSAs	Population, population density, age, race, income	A 10-percent reduction in minimum biweekly sulfate and mean biweekly particulates associated with 0.91-percent reduction in mortality	Lave and Seskin, 1973
Sulfur dioxide	Chicago, Denver, Philadelphia, St. Louis, Washington, D.C.	Weather, day of the week	A decrease of 0.092 ppm in the mean concentration of sulfur dioxide associated with a decrease of 63 deaths per day (Chicago)	Lave and Seskin, in press
Sulfur dioxide	U.S. SMSAs	Temperature, precipitation, humidity, age, race, six socioeconomic factors	Sulfur dioxide found significant in explaining mortality rates	McDonald and Schwing, 1973
Sulfates	U.S. SMSAs; male, white, over 65	Various climatic, demographic, and socioeconomic factors	Found significant association between sulfates and mortality from arteriosclerotic heart disease and cancer of respiratory and gastrointestinal tract	Sprey and Takacs, 1973
Particulates, sulfur dioxide	New York City	Weather	Found significant association between sulfur dioxide and particulate levels and mortality from respiratory and heart disease	Hodgson, 1970
Smoke shade, sulfur dioxide	New York City	Weather	Found association of daily mortality with sulfur dioxide stronger than with any weather variable	Glasser and Greenburg, 1971
Smoke shade,	New York City	Weather, day of the week	Between 18.12 - 36.76 excess deaths per day associated with air pollution; 80 percent of effect ascribed to smoke shade, 20 percent to sulfur dioxide	Schimmel and Greenburg, 1971
Sulfur dioxide	New York Metropolitan region	Temperature, epidemics, disasters, holidays, day of the week, time trends	Found association between sulfur dioxide levels and residual mortality	Buechley et al., 1973
Particulates	Buffalo, N.Y.	Age, sex, race, income	Mortality from chronic respiratory disease found twice as high at high as at low particulate levels	Winkelstein et al., 1967
Particulates	Buffalo, N.Y.	Age, sex, race,	Mortality from gastric and prostatic cancer found twice as high at high as at low particulate levels	Winkelstein and Kantor, 1969a, 1969b
Particulates	Buffalo, N.Y.	Age, sex, race, income	Found association between particulate levels and mortality from arteriosclerotic heart disease, cerebrovascular disease, and cirrhosis of the liver	Winkelstein and Gay, 1971
Particulates, soiling, dust, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between soiling and sulfur dioxide and total morbidity and cardiovascular disease morbidity; association between sulfation, dustfall, and particulates and cardiovascular disease in females	Zeidberg et al., 1964
Particulates, soiling, dust, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between particulates and cardiovascular mortality in females; association between soiling and sulfation and mortality from respiratory disease but not lung cancer	Zeidberg et al., 1967a, 1967b

Table 2 (continued)

Pollutants	Target Population	Covariates	Results	Reference
Particulates, soiling, dush, sulfur dioxide, sulfation	Nashville, Tenn.	Age, sex, race, income	Found association between pollutant levels and total cancer mortality and cancer of esophagus, stomach and bladder, but not lung cancer	Hagstrom et al., 1967
Particulates, sulfur dioxide	Los Angeles	Weather	Found significant association between pollutant levels and disease-specific hospital admissions and lengths of stay	Sterling et al., 1966, 1967. 1969
Soiling	Allegheny County (Pittsburgh)	Weather, day of the week	Doubling of soiling index associated with 22-percent increase in admissions for respiratory emergency	Silverman, 1973
Particulates, sulfation	Berlin, N.H. and Chilliweek, B.C.	Smoking	Found association between particulate and sulfation levels and incidence of chronic respiratory disease	Ferris and Anderson, 1962, 1964; Anderson et al., 1965; Ferris et al., 1973
Nitrogen dioxide	Chattanooga school children	Smoking, socio-economic	Rates of acute respiratory illness found higher in areas with high NO_2 levels	Shy et al., 1970a, 1970b, 1973
Nitrogen dioxide	Chattanooga school children	Years of exposure	Found association between exposure to NO_2 and incidence of bronchitis	Pearlman et al., 1971
Nitrogen dioxide	Parents of Chattanooga school children	Smoking, ages, sex, race	No association found between NO_2 and chronic bronchitis	Chapman et al., 1973
Nitrogen dioxide	U.S. SMSAs, white males and females over 65	Weather, socio-economic	Mortality from hypertensive heart disease increased by about 200 per 100,000; lung cancer increased by 50 percent for males, and 130 percent for females upon increasing NO_2 levels from 0.03 to 0.08 ppm	Sprey and Takacs, 1973
Photochemical oxidants	School children in Los Angeles		Found no significant association between oxidant levels and school absenteeism due to respiratory illness	Wayne and Wehrle, 1969
Photochemical oxidants	Student nurses in Los Angeles	Nitrogen dioxide, carbon monoxide, temperature	Developed thresholds for several health symptoms	Hammer et al., 1974
Carbon monoxide	Los Angeles County	Oxidants, temperature	Found significant association between daily mortality and carbon monoxide, but not oxidants	Hexter and Goldsmith, 1971
Carbon monoxide			Found association between carbon monoxide and angina and intermittent claudication	Aronow et al., 1972, 1973, 1974
Non-specific air pollution	Students at 7 California universities	Climatic and socioeconomic variables, holidays, chronic conditions	Found association between air pollution and excess incidence of respiratory illness	Durham, 1974
Benzo-a-pyrene	U.S. and 19 other countries		An increase of 1 ug/1000 m^3 in concentration of benzo-a-pyrene was associated with 5-percent increase in mortality from lung cancer	Carnow and Meier, 1973
Oxidants, nitrogen dioxide, carbon monoxide	California		Developed a series of dose-effect functions on the basis of expert opinions	Leung et al., 1975

investigated are sulfur oxides and particulates, photochemical oxidants, carbon monoxide, and unspecified air pollutants. Sulfur oxides and particulates are considered jointly because of their strong synergistic effects on health. The actual causative agent is probably some combination of sulfur dioxide, acid sulfates, and other particulates.

A wide variety of health effects are explored in these investigations. The principal effects are mortality and morbidity (i.e., incidence and prevalence of disease), but each of these may be further characterized by various specific diseases and measured by a number of indicators. The diseases are respiratory and cardiovascular dysfunctions, neoplasms of the respiratory and gastrointestinal tracts, chronic nephritis, and impaired fetal development and mental function. The indicators of morbidity include work and school absenteeism, hospital admissions and residence days, doctors' visits, and personal histories.

2. Sulfur Oxides and Particulates

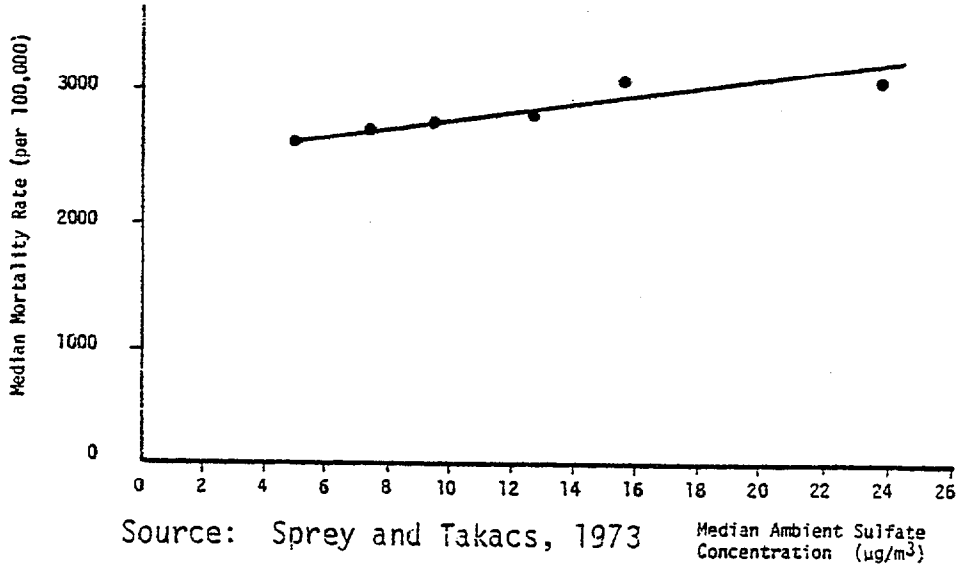
A number of important cross-sectional studies have compared the effects of sulfur oxides and particulates on populations of metropolitan areas. Lave and Seskin (in press) investigated the relationship between sulfate and particulate pollution and mortality rates in more than 1.00 SMSAs, using multivariate regression analysis and controlling for age, racial composition, population density, income, and geographic size of SMSA. The most significant pollution variables were the minimum biweekly sulfate and the mean biweekly particulate levels. Increase of 1 $\mu g/m^3$ in the former (raising the mean from 4.72 to 5.72 $\mu g/m^3$) was associated with an increase of 6.3 per 100,000 in the total death rate, whereas an increase of 10 $\mu g/m^3$ in the latter (raising the mean from 118-1 to 128.1 $\mu g/m^3$) was associated with an increase of 4.5 per 100,000 in the total death rate.

A significant relation between daily SO_2 levels and daily mortality in Chicago was found by Lave and Seskin (in press) in a study of SO_2, NO, NO_2, CO, and hydrocarbons in five cities (Chicago, Denver, Philadelphia, St. Louis, and Washington, D.C.). A regression including current and lagged values of SO_2, three weather factors, and day of the week, associated a decrease of 50 percent in SO_2 level with a

decrease of 5.5 percent in daily deaths. A significant relation was also found for NO in Chicago. A study by Cannow et al. (1969) in Chicago showed a similar association between mortality from respiratory diseases and SO_2 levels, but an earlier study of the same variables by Burrows et al. (1968) found no such relation.

In another analysis of data from SMSAs, McDonald and Schwing (1973) employed a ridge regression analysis to investigate the association between air pollution potential and mortality rates, including a number of climatic and socioeconomic variables. The variable representing sulfur dioxide was quite significant in explaining variations in the mortality rate between SMSAs in spite of the ridge transformation. However, data for SO_2, NO_x, and HC were deficient and the authors used "pollution potentials", based on pollutant emissions and weather factors, rather than ambient air concentrations. The relationship of these potentials to actual pollutant levels is not known, so that the results contribute only supportive evidence.

An application of nonparametric analysis to cause-specific mortality statistics for 42 SMSAs (Sprey et al., 1973) revealed a positive correlation of mortality from arteriosclerotic heart disease and neoplasms of the respiratory and gastrointestinal tracts with sulfate levels. For white males over 65, an increase in median sulfate concentrations from 5 $\mu g/m^3$ to 24 $\mu g/m^3$ was associated with a 19 percent increase in mortality from arteriosclerotic heart disease (see Figure 3).

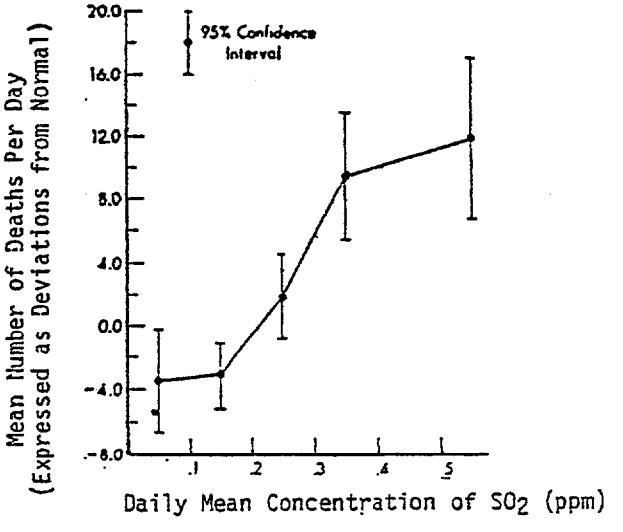


Source: Sprey and Takacs, 1973

Figure 3. Relationship Between Median Ambient Sulfate Concentration and Median Mortality from Arteriosclerotic Heart Disease

A number of daily time series studies were made in New York City and its metropolitan area. A study of short-term effects by Hodgson (1970) used multiple regression to analyze the relationships among mortality, air pollution (particulates and sulfur dioxide), and several meteorological factors. Mortality from respiratory and heart diseases for all ages was found to be significantly related to the level of air pollution. However, any detailed analysis of the acute effects of pollution was frustrated by the employment of moving averages of the variables.

Glasser and Greenburg (1971) found a definite relationship between deviations from a five-year "normal" in New York City's daily mortality, and daily mean concentration of sulfur dioxide (see Figure 4). In a regression analysis including sulfur dioxide, rainfall, wind speed, sky cover, and temperature deviations as explanatory variables, the respective beta coefficients were 0.292, 0.024, 0.015, and 0.061. These coefficients were independent of measurement units and could form the basis for a dose-effect function. Glasser and Greenburg measured mortality in terms of deviations from a 15-day moving average. This measure is suggestive of cycles in the data and of lags in the effects of pollution, but lagged variables were never utilized and the investigation never questioned the timing of the effect.



Source: Glasser and Greenburg, 1971

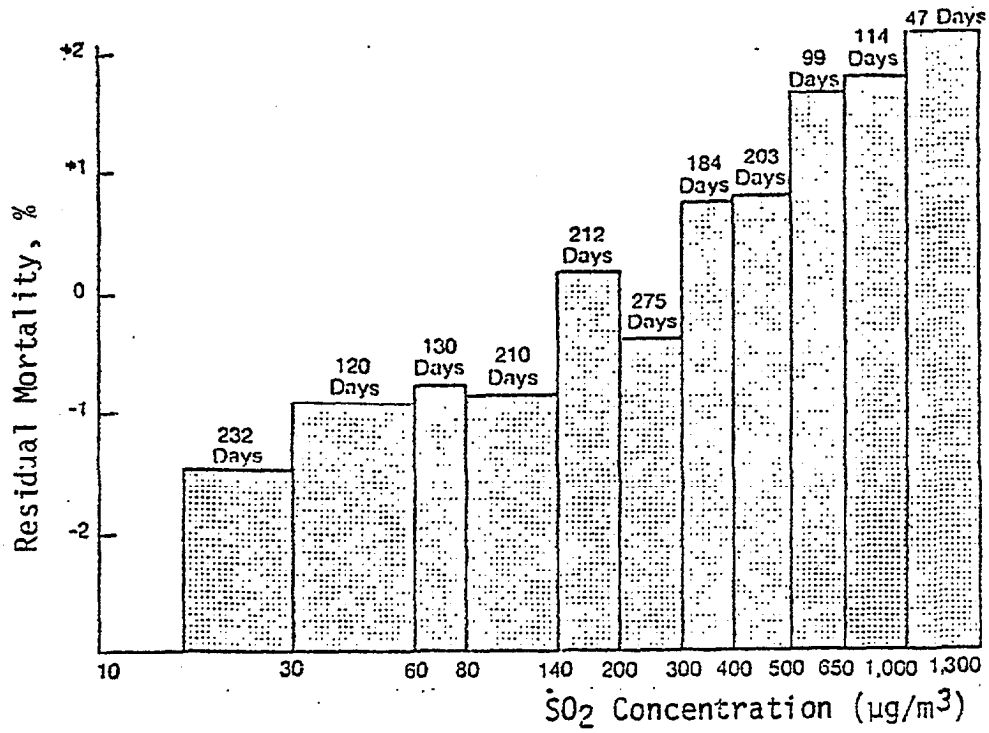
Figure 4. Relationship Between Mean Number of Deaths and Mean SO_2 Concentration in New York City

Schimmel and Greenburg (1972) performed a similar analysis for New York City. Using a linear model, they regressed daily mortality on sulfur dioxide and smoke shade levels for the same and previous days, while controlling for weather factors and day-of-the-week effects, They concluded that, if air pollution in New York City were reduced to zero, there would be, on the average, from 18.12 to 36.74 fewer deaths each day, depending on the particular pollution variate under consideration. This represents about 12 percent of the over half-million deaths occurring during the six-year study period. Furthermore, in looking at the individual effects of the two pollutants, they concluded that 80 percent of the excess deaths could be attributed to smoke shade, and only 20 percent to sulfur dioxide.

The method of analysis was novel and deserves comment. Instead of including measures of climate and other factors as independent variables in the regressions, Schimmel and Greenburg adjusted the air pollution variables to remove these effects. The adjustment was employed to eliminate spurious associations. However, in eliminating most of the variations in the air pollution variables, the technique results in biased estimates of the effects of air pollution on mortality. Any use af their findings for the construction of dose-effect functions must be made with this in mind.

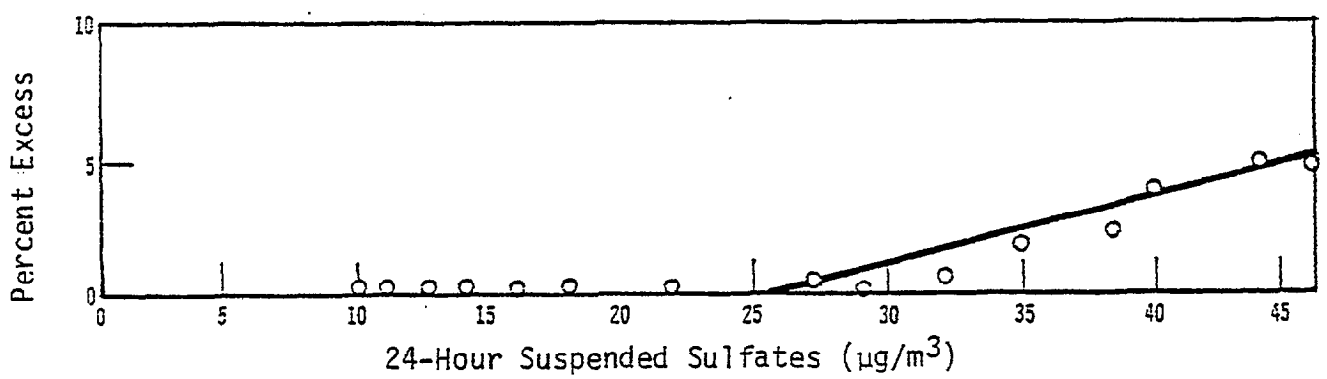
Buechley et al. (1973) used multiple regression to analyze the relationship between daily mortality and sulfur dioxide levels in the New York-New Jersey metropolitan region between 1962-1966. The analysis controlled for temperature, holidays, day of the week, and epidemics, and eliminated "disasters and time trends". Residual mortality values (observed minus predicted mortality) were found to follow a gradient with classes of SO_2 concentrations {see Figure 5). The effects of coefficient of haze (COH) were discussed, but no quantitative assessment was presented.

Schimmel and Murawski (1975) and Buechley (1975) have recently offered a re-evaluation of their New York City data. Both reach the conclusion that SO_2 was a proxy for some other factor and not the causal agent. Schimmel and Murawski state:



Source: Buechley et al., 1973

Figure 5. Relationship Between Classes of SO_2 Concentration and Mean Residual Mortality in New York City - New Jersey



Source: Adapted from Finklea et al., 1975

Figure 6. Relationship Between Sulfate Levels and Excess Mortality

> "Our statistical studies, as well as those of Dr. Buechley, suggest that SO_2 is not only serving as an indicator of air quality but also that SO_2 is not an injurious pollutant, at least at the ambient levels encountered in New York City in the 1960's--namely, average levels of 0.2 ppm (525 Mg/m^3) and peak levels of 0.6 ppm (1575 Mg/m^3). This is entirely consistent with results of published data on the effects of SO_2 on humans and animals."

The results obtained by Schimmel and Greenburg (1972) and by Buechley et al. (1973) were combined by Finklea et al. (1975) in a form which recognized only excess mortality, at SO_2 levels above normal, and employed an empirical equation to convert SO_2 measurements into sulfate equivalents. The lower-than-average mortalities at low SO_2 levels which appear in both of the original publications were treated as zero excess mortality. The function is shown in Figure 6 and may be expressed by the equation:

$$\text{Percent excess mortality} = 0.25\ (\text{sulfate concentration above } 25\ \mu g/m^3)$$

A series of studies in and around Buffalo, New York, by Winkelstein and colleagues focused on particulate pollution. The populations at risk were white males and females, 50-69 years old, and results were developed for five levels of family income. Effects studied were mortalities from chronic respiratory disease (asthma, bronchitis, emphysema), gastric cancer, prostatic cancer, arteriosclerotic heart disease, and cirrhosis of the liver. These studies offer a great deal of useful material for the development of damage functions. A majority of the sets, male and female, show an increase in mortality with rising pollution and income level. The studies are discussed below and the results are summarized in Table 3.

Winkelstein et al. (1958) performed a similar study using oxides of sulfur as the pollution measure. A positive association was found between sulfation and chronic respiratory disease mortality in the two lowest economic groups, the only ones with sufficient data. Winkelstein and Kantor (1969a, 1969b) found the rate of mortality from both gastric and prostatic cancer more than twice as high in polluted areas as in relatively clean ones. Winkelstein and Gay (1971) found a consistent

Table 3. Mortality Rates (per 100,000) At Several Pollution and Income Levels in Buffalo

Median Income \ Particulate Level in $\mu g/m^3$/day	< 80	80-100	100-135	> 135
I	-	126 [a/]	271	392
3005-5007	-	0(0) [b/]	63(33)	136(24)
	18 [c/]	26	38	39
	-	1572(366) [d/]	1647(652)	1774(1029)
	-	129(0) [e/]	129(37)	359(69)
II	136	154	172	199
5175-6004	45(8)	41(18)	48(25)	84(40)
	-	-	-	-
	191(388)	1115(436)	1234(534)	1350(689)
	28(11)	82(19)	144(30)	173(47)
III	-	-	-	-
6013-6614	-	39(30)	51(16)	51(49)
	18 [f/]	23	33	51
	-	1024(400)	1045(460)	1387(540)
	-	48(17)	87(25)	81(57)
IV	70	80	177	-
6618-7347	15(5)	38(21)	63(0)	-
	-	-	-	-
	820(345)	1066(346)	1149(493)	-
	37(31)	33(21)	83(27)	-
V	79	109	0	-
7431-11792	26(14)	16(9)	0(0)	-
	-	-	-	-
	789(290)	1917(320)	697(197)	-
	26(11)	17(17)	95(0)	-

a/ Asthma, bronchitis, emphysema, white males, 50-69
b/ Gastric cancer, white males (females), 50-69
c/ Prostatic cancer, white males, 50-69, income levels I and II
d/ Arteriosclerotic heart disease, white males (females), 50-69
e/ Cirrhosis of the liver, white males (females), 50-69
f/ Prostatic cancer, white males, 50-69, income levels III, IV, and V

Source: Winkelstein et al., 1967, 1968; Winkelstein and Kantor, 1969a, b; Winkelstein and Gay, 1971

gradient for arteriosclerotic heart disease from the lowest to the highest pollution level, except in the highest economic class. Results were similar, though less consistent, for cerebrovascular disease. A graded positive association was found between suspended particulates and cirrhosis of the liver.

Zeidberg et al. (1964) found significant associations of total morbidity and cardiovascular disease morbidity with soiling index and sulfur dioxide in males in Nashville, Tennessee. Cardiovascular disease morbidity in females showed a direct relationship with sulfur dioxide, sulfation, soiling, dustfall, and suspended particulates, (see Table 4). For cardiovascular mortality, a regular pattern was noted for females but not for males (Zeidberg et al., 1967). Zeidberg et al. (1967) found that total respiratory disease mortality in Nashville was directly related to sulfation and soiling, but death rates for other specific diseases followed no definite pattern, and socioeconomic differences could not explain the observed associations (see Table 5).

Hagstrom et al. (1967) found total cancer mortality to be generally higher in polluted than in relatively clean areas of Nashville, Tennessee (see Table 5). They also found significant mortality rate increases associated with cancer of the stomach, esophagus, and bladder. However, they were unable to isolate an air pollution effect on lung cancer mortality. These findings parallel the cancer observations in Buffalo.

Studies of hospital admissions in Los Angeles and a range of pollutant indices have shown that diseases rationally connected with air pollution do in fact show some correlations, especially with SO_2 and particulates, and NO_x and oxidants (Brant and Hill, 1964; Brant, 1965; Sterling et al., 1966, 1967, 1969). However, the results were not presented in a manner useful for the construction of dose-effect functions.

Using multivariate statistical analysis techniques, Silverman (1973) studied daily emergency admissions at hospitals in Allegheny County for treatment of respiratory diseases (particularly bronchitis and

Table 4. Mortality Rate (per 100,000) at Several Pollution Levels in Nashville

Pollution Indicator \ Pollution Level	Low	Moderate	High
Sulfation ($mg/100\ cm^2/day$)	≤ 0.150	0.151-0.350	≥ 0.351
	126.3(160.0)[a/]	114.9(134.2)	192.0(168)
	36.2(31.1) [b/]	34.1(40.4)	64.0(45.8)
Soiling (COHS)	≤ 0.330	0.331-0.830	≥ 0.831
	95.6(126.7)	122.4(138.9)	140.3(157.8)
	20.4(16.2)	35.0(38.1)	52.8(55.2)
Dustfall ($T/mi.^2/mo$)	≤ 5.00	5.01-15.00	≥ 15.01
	84.8(123.7)	135.0(146.4)	116.7(150.0)
	31.6(28.9)	39.0(42.0)	16.7(50.0)
Particulates ($\mu g/m^3/24$ hrs.)	≤ 100	101-199	≥ 200
	139.4(123.7)	107.9(127.0)	130.4(176.4)
	41.1(36.3)	36.1(38.0)	26.1(52.8)
Sulfur Dioxide (ppm/24 hrs.)	≤ 0.0050	0.0051-0.0100	≥ 0.0101
	80.6(115.8)	116.9(135.6)	177.4(171.8)
	22.2(28.9)	36.8(36.8)	47.2(51.8)

a/ All causes, white middle-class males (females), ≥ 55

b/ Cardiovascular disease, white middle-class males (females), ≥ 55

Source: Zeidberg et al., 1964

pneumonia) and found that a doubling of the soiling index was associated with a 22 percent rise in admissions. The air pollution variable was also associated, to a much lesser degree, with emergency heart disease admissions, but not with emergency admissions for deliveries, appendectomies, and other problems. A similar study of demand on health services for diseases aggravated by air pollution was made by Jaksch (1973), who found an association with suspended particulate concentrations.

Table 5. Mortality Rate (per 100,000) at Several Pollution Levels in Nashville

Pollution Indicator \ Pollution Level	Low	Moderate	High
Sulfation ($mg/100\ m^2/day$)	≤ 0.150	0.151-0.399	≥ 0.400
	71.59	76.59	125.19 a/
	144.66	128.92	149.95 b/
Soiling (COHS)	≤ 0.350	0.351-1.099	≥ 1.100
	67.31	75.22	119.00
	123.75	129.99	152.59
Dustfall ($T/mi.^2/mo.$)	≤ 5.00	5.01-11.99	≥ 12.00
	77.48	74.92	118.47
	130.91	129.83	145.35
Sulfur Dioxide (ppm/24 hrs.)	≤ 0.005	0.006-0.012	≥ 0.013
	99.54	71.29	117.74
	138.40	129.06	140.70

a/ All respiratory disease, middle class, age-adjusted

b/ All cancer, middle class, age-adjusted

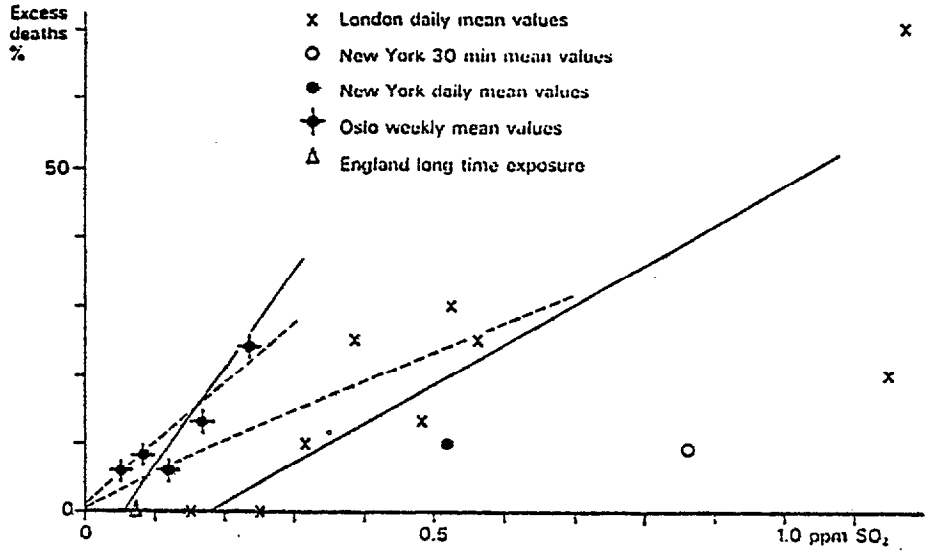
Source: Zeidberg et al., 1967; Hagstrom et al., 1967

A classic illustration of a cross-sectional epidemiologic study is the work of Ferris and Anderson in Berlin, New Hampshire, and Chilliwack, British Columbia (Ferris and Anderson, 1962, 1966; Anderson et al., 7965; Ferris et al., 1973). The incidence of chronic respiratory disease (bronchitis) and lung function were measured and smoking was controlled. A follow-up of the initial Berlin study for the period 1961-1967 found that a decrease of 30-40 percent in particulate level and sulfation yielded a reduction in chronic respiratory disease. Interpretation of these results should be tempered by awareness of the poor quality of the data and the likely socioeconomic differences between the two locations.

Goldberg et al. (1972) failed to find a significant association of particulate pollution with health in three southeastern schools. However, this may have been due to the index of effect, which was absence rate. Absence is known to be significantly affected by variables other than health.

Epidemiologic studies of U.S. EPA's Community Health and Environmental Surveillance System (CHESS) program have provided dose-effect information on morbidity associated with exposure to sulfur dioxide and other air pollutants. Health indicators employed for long-term effects were prevalence of chronic bronchitis in adults, incidence of acute lower respiratory infection in children, acute respiratory illness in families, and decreases in vastilatory functions of children. The short-term indicators were aggravation of cardiopulmonary symptoms and of asthma. The results support the long-term air quality standards, but indicate that the short-term standards may be too high. CHESS studies have been criticized for inadequate sample size, selected population groupings, and failure to investigate non-respiratory effects. (U.S. EPA, 1974).

The applicability of damage functions observed abroad to U.S. environmental policy decisions is questionable, as comparisons with European data show wide discrepancies. This is illustrated in Figure 7, which reports the relationship between SO_2 concentration and percent excess deaths for New York, London, and Oslo. The two solid lines are drawn through the London and Oslo data, respectively, assuming the existence of thresholds, whereas the corresponding dashed lines make no such assumption. These differences may be due in part to different sampling and analysis techniques, but differences in population characteristics and way of life are probably also significant (Royal Ministry, 1972). Extensive studies in London, where particulate pollution (smoke shade) has decreased more than fivefold in two decades, while SO_2 has only decreased slightly, reveal that the earlier trend of decreasing total and respiratory mortality and morbidity has not been sustained subsequently (Lawther, 1963; Martin, 1964; Fletcher et al., 1968). This is consistent with the situation in New York as reported by Buechley (1975).



Source: Swedish Royal Ministry, 1972

Figure 7. Relationships Between SO_2 Concentration and Excess Deaths in New York, London, and Oslo

3. Nitrogen Oxides

The effects of nitrogen oxides on human health have received relatively little attention, perhaps because of the difficulty of measuring ambient concentrations and the lack of reliable historical data. Consequently, permissible levels of nitrogen dioxide are based on less than adequate evidence.

The best known epidemiologic studies of the effect of nitrogen dioxide (NO_2) on human health were conducted by Shy et al. (1970a, 1970b) at Chattanooga, Tennessee, where emissions from a chemical factory provided an opportunity to compare incidence of acute respiratory disease in areas of high, intermediate, and low NO_2 levels. The health data covered the period of 1968-1969, but the corresponding NO_2 data, obtained by the Jacobs-Hochheiser technique, were considered unreliable and were replaced by 1967-1968 NO_2 data measured by the Saltzman method (Shy et al., 1973). The new data are reported in Table 6 for the low and intermediate areas, as well as for the three schools and nearby sampling stations in the high NO_2 area.

Table 6. Respiratory Illness at Various NO_2 Levels in Chattanooga

Areas	Low	Intermediate	High 1	High 2	High 3
NO_2, $\mu g/m^3$	56	113	282	150	150
Individuals Affected:	Excess Illness, As Percent of Low Area				
All Family	0	- 7.3	18.0	16.7	8.7
Second Graders	0	-10.5	16.4	16.4	1.0
Siblings	0	- 8.2	17.1	5.9	12.4
Mothers	0	- 4.1	24.4	17.1	8.9
Fathers	0	- 8.3	14.6	33.3	26.0

Source: Shy, C.M., et al., 1970a, 1970b, 1973

It should be noted that rates of respiratory disease are not consistently correlated with exposure gradient among the three schools in the high exposure area, whereas rates in the intermediate control area are lower than in the low control area. The results could not be explained by prevalence of chronic conditions, differences in family composition, economic level, or education of family head. Parental smoking habits did not appear to influence respiratory illness rates among children. Meteorological factors were not controlled in the analysis. The study has been criticized by Warner and Stevens (1973) because no attempt was made to control for acid mists, which were probably present in significant concentrations.

A study by Pearlman et al. (1971) of the areas designated by Shy et al., with controls for years of exposure, found that one or more episodes of bronchitis were reported significantly more often by school children residing for two and three years in the high and intermediate NO_2 areas (see Table 7). Neither morbidity from croup and pneumonia, nor reported hospitalization for lower respiratory illness differed significantly among the three areas. In another study at Chattanooga, Chapman et al. (1973) found no association between current or past pollution levels and the prevalence of chronic respiratory disease among parents of high school students residing in three exposure areas.

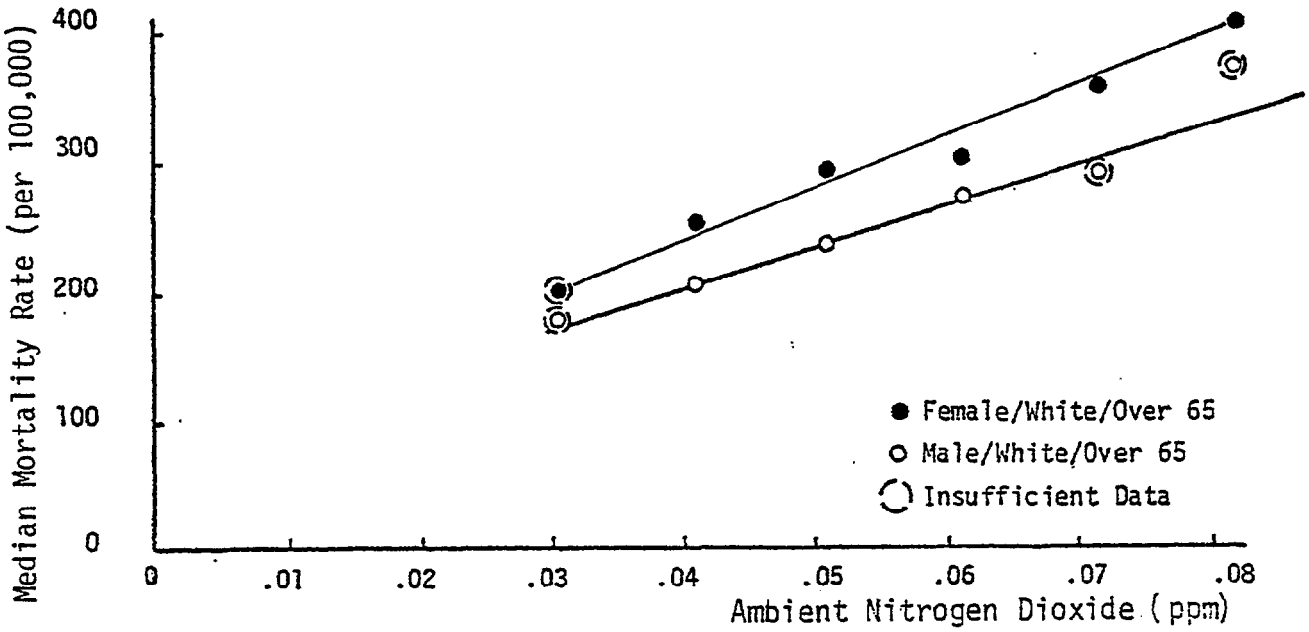
Table 7. Incidence of Bronchitis Among Chattanooga School Children at Various Pollution Levels

Areas	Pollutant				Percent Reporting One or More Episodes		
	NO_2 (ppm)	Nitrates ($\mu g/m^3$)	Sulfates ($\mu g/m^3$)	Particulates ($\mu g/m^3$)	Years of Exposure 1	2	3
Low	.043	1.6	10.0	62	25.1	20.3	23.2
Intermediate	-063	2.6	9.8	72	31.6	45.5	31.2
High	.083	5.8	11.5	81	20.9	34.7	32.2

Source: Pearlman, M.F., et al., 1971

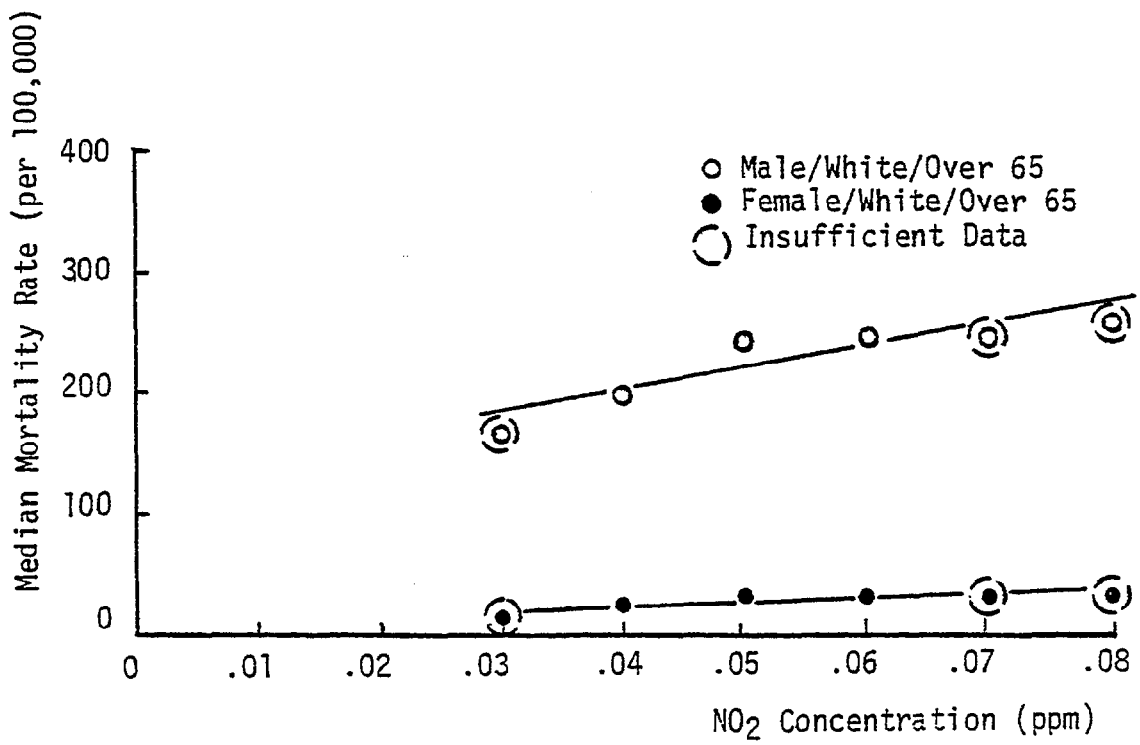
Sprey and Takacs (1973) studied annual data on pollution, climatology, mortality, and socioeconomic characteristics for 42 SMSAs with the aid of single-variable analysis of the median disease-specific mortality rates and found a strong association between NO_2 levels and mortality from hypertensive and arteriosclerotic heart disease and lung cancer (see Figures 8 and 9). Analysis of independent age groups and of pooled variables failed to weaken the association with hypertensive heart disease, but the association with arteriosclerotic heart disease was shown to be due to the interrelationship of nitrogen dioxide levels and ambient sulfate levels. Increases in NO_2 level from 0.3 to 0.8 ppm were associated with approximately 200 more deaths per 100,000 from hypertensive heart disease for white males or females over 65, with 50 and 130 percent increases in lung cancer death rates for white males over 65, and white females over 65, respectively.

Other oxides of nitrogen may have a significant role in pollution chemistry, but the epidemiologic evidence is scarce. Lave and Seskin (1975) found an association between nitric oxide (NO) levels and daily mortality in Chicago as part of their five-city study. Sterling et al. (1966, 1967, 1969) found an association between nitrogen oxides (and other pollutants) in Los Angeles and daily hospital admissions.



Source: Sprey et al., 1974

Figure 8. Relationship Between NO_2 Concentration and Median Mortality from Hypertensive Heart Disease



Source: Sprey et al., 1974

Figure 9. Relationship Between NO_2 Concentration and Median from Lung Cancer

4. Oxidants

Only two studies of the effects of photochemical oxidants on human health were found to meet all of the selection criteria set forth in Section A 1: a study of school absenteeism by Wayne and Wehrle (1969) and one of student nurses by Hammer et al. (1974).

Wayne and Wehrle (1969) examined the association between daily oxidant levels and school absenteeism at two elementary schools in Los Angeles. They were unable to detect a statistically significant relationship between absences due to respiratory illness and concurrent or previous day's oxidant levels.

Hammer et al. (1974) compared the daily percent of students reporting each of several symptoms in two Los Angeles nursing schools with daily maximum measurements of photochemical oxidants, carbon monoxide, and nitrogen dioxide, as well as temperature. Incidence of symptoms could not be attributed to carbon monoxide, nitrogen dioxide, or maximum temperature. However, threshold functions for symptom rates were developed in relation to photochemical oxidants (see Table 8). The study concluded that the national standard for photochemical oxidants provides little or no margin of safety for the symptoms observed. These findings would have been even more convincing if other factors, such as day-of-the-week effects had been controlled.

Table 8. Oxidant Thresholds For Various Symptoms

Symptom	Oxidant Threshold (ppm)
Headache	0.5
Eye Discomfort	0.15
Cough	0.26
Chest Discomfort	0.30

Source: Hammer, et al., 1974